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An Efficient and Reliable Tree-based Anti-collision Protocol for RFID Systems with Capture Effect

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Abstract—**In radio frequency identification (RFID) systems, if tags transmit their IDs simultaneously, a reader cannot correctly identify the IDs due to collision and the performance of RFID systems degrades by the collision. So, anti-collision protocols to reduce the number of collisions are required. The binary tree anti-collision protocol branches randomly in a tree to reduce collisions in the next identification process when the IDs are not identified after sending the IDs of tags. The channel condition may change due to the distance between a reader and a tag, noise or interference from he IDs of tags in the binary tree protocol. When a tag is identified by the capture effect, the tags in the same slot may lose the opportunity for identification. Thus, we propose an efficient and reliable binary tree-based anti-collision protocol considering channel errors and the capture effect. We derive the total time slots of the proposed protocol analytically and show the performance of RFID systems for the proposed protocol through simulations.**

Keywords—Radio frequency identification (RFID), anti-collision, channel error, capture effect

I. Introduction

In Radio Frequency IDentification (RFID) systems, each tag sends an identifier (ID) to a reader to deliver its information. When there are a large number of tags in a reading area of the reader, to transmit IDs independently may cause a collision[1]. Then, the reader cannot read the information correctly due to a collision. If a collision of tags occurs, the collided tags have to try again and consume additional slots. In an attempt to tackle the problem many researches have been conducted to present anti-collision protocols to enhance the performance of RFID systems by reducing collisions[2], [3].

Tag anti-collision methods are classified into two types. ALOHA-based[4] and tree-based[5]. ALOHA-based algorithms such as Framed Slotted ALOHA (FSA) and Dynamic Framed Slotted ALOHA (DFSA)[6] divide a frame by a plurality of slots and each tag randomly selects a slot. FSA fixes the frame size and tags choose a slot randomly among the slots in the frame, and DFSA estimates the number of tags to control the frame size[7]. However, in an ALOHA-based algorithm, collided tags compete again. A tree-based algorithm separates a collided slot into two slots to which collided tags randomly try retransmission. The operation is repeated until all tags are recognized[3], [5].

Passive RFID tags receive continuous wave (CW) from a reader and reflect the CW by backscattering to send information. The backscattering signals are weak and they can be influenced significantly by noise or interference in a practical environment[8], [9], [10] and the reader may not identify IDs from tags. However, most of researches have been studied under the ideal channel condition. So, a suitable protocol for actual channel model with channel errors is required. In addition, we have to consider the capture effect as well as channel errors in a practical channel environment. The capture effect may occur during the tag identification process [11], [12], [13] when a tag with the most strong signal intensity is identified among multiple tags transmitting in the same slot. The probability of the capture effect can affect the performance of an RFID system and it needs to be taken into consideration [13].

Generalized Binary Tree (GBT) is a binary tree-based protocol with the capture effect [14]. If tags transmit their IDs simultaneously, a tag may be identified by the capture effect despite of the collision. However, after the capture effect, unidentified tags try to be identified again by a binary tree in the next cycle until there are no unidentified tags. This is not efficient since unidentified tags have to be retransmitted. In this paper, we study the performance of a tree-based anti-collision protocol under a practical channel model. In order to improve the performance in the practical channel environment, we propose an efficient and reliable binary tree-based anti-collision protocol for RFID systems. The proposed protocol can save wasted time slots and identify tags quickly even in the channel errors and capture effect.

II. Proposed Anti-collision Protocol with Capture Effect

In this section, we propose and explain an efficient and reliable binary tree-based anti-collision protocol. There are a reader and multiple passive tags in an RFID system and the tags send their IDs to the reader as in Fig. 1. The signal strength depends on the distance between a reader and a tag. In Fig. 1, solid lines denote continuous wave signals from the reader whereas dotted lines denote backscattering signals reflected from the tags. The thickness of a line indicates the strength of a signal. The received power at a reader is [8].

$$P_{RX}(d_i) = \alpha \cdot \frac{P_{TX} \cdot G_{reader}^2 \cdot \lambda^4 \cdot G_{tag}^2}{(4\pi d_i)^4} \cdot 0.25, \qquad (1)$$

where d_i is the distance between a reader and tag i, P_{TX} is transmission power of a reader's continuous wave, G_{reader} is the antenna gain of a reader, G_{tag} is the antenna gain of a tag, λ is the wavelength of a signal, α is the influence of the load impedance mismatch on the amount of re-radiated power ($\alpha =$

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1), 0.25 is the portion of the tag signal from the total reflected power.

In a binary tree protocol tags start from the transmission count 0. The unidentified tags transmit their IDs with information when their transmission count becomes zero. If a tag receives the valid ACK within a specified period of time, the tag is aware of its own identification by the reader and stays until receiving the query command again. Other tags hearing the ACK of another tag are conscious of successful identification of the tag and they reduce their transmission counts by 1. If a tag does not receive the valid ACK within a specified period of time, it realizes that its ID is not identified and selects the transmission count zero or one randomly. The other tags not involved in the collision increases the transmission counter by 1.

The reader decides the state of a slot when tags send their IDs to the reader. The states of a slot are as follows.
$success$: only one tag successfully sends its ID to the reader without error.
$failure$: more than one tag send their IDs to the reader simultaneously without capture effect.
$channel\ error$: only one tag sends its ID to the reader but it’s not identified due to channel error.
$capture\ effect$: more than one tag send their IDs to the reader simultaneously but a tag is identified by the capture effect.
$idle$: tags do not send their IDs.

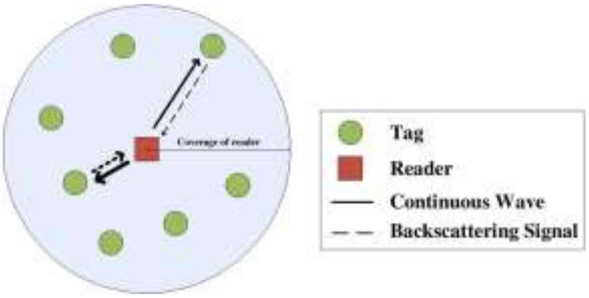

Figure 1. Backscattering in an RFID system.

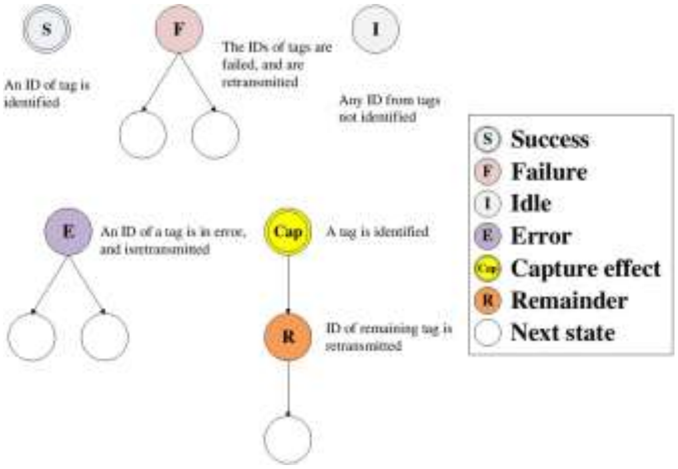

Figure 2. The states of tags.

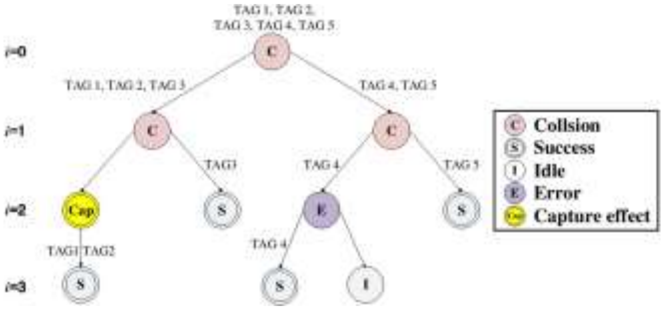

Figure 3. Operation example of the proposed protocol.

If a channel error occurs, the tag retransmits its ID to the reader at the next slot. The slot is either $success$, $idle$ or $error$. If the capture effect occurs, a tag is successful and the other colliding tags are retransmitted at the next slot. The slot is either $success$, $failure$ or $error$.

We explain how a reader identifies tag IDs from the tags in an environment with channel errors and the capture effect. First, we present an identification procedure when a channel error occurs at a slot. When a reader cannot correctly identify an ID from a tag due to channel error, the reader informs all tags that the ID is not identified at the preceding slot. Then, all tags increase their transmission counts by one except for the unidentified tag. And the tag retransmits its ID immediately at the next slot. Thus, the tag can be identified even in the channel error condition. Next, we present an identification procedure when the capture effect occurs at a slot. When multiple tags send their IDs to the reader in the same slot, the reader recognizes that the capture effect occurs in the slot by detecting the signal energy level from the tags [15]. When the reader transmits the ACK message of a specific tag, all tags receive the information and are aware of the capture effect. They increase the transmission count by one except for the tags that have attempted transmission at the former slot. So, the colliding tags immediately retransmit at next slot. So, the colliding tags have an opportunity to be tag identified quickly than the other tags. If the capture effect does not occur in the multiple tags’ transmission, the slot becomes a collision slot. The colliding tags retransmit their IDs at one of the next two slots.

We explain an example of the identification process. There are five tags and a reader. All tags send their IDs at slot 0, and collision occurs at the slot. The tags know that their IDs are not identified at the slot. The failed tags select the transmission count ‘0’ or ‘1’ randomly. Three tags (i.e., TAG 1, TAG2, and Tag 3) select 0 and two tags (i.e., TAG 4 and Tag5) select 1. Three tags with transmission count 0 send their IDs at slot 1. However, they suffer from collision and select the transmission count again. Two tags (i.e., TAG 1 and TAG 2) with transmission count 0 retransmit their IDs at slot 2. Despite of the concurrent transmission, TAG 1 is identified by the capture effect whereas TAG 2 is not identified. The reader successfully identifies the ID from TAG 1 and sends an ACK on the identification of TAG 1. Then, TAG 2 recognizes that its ID is not identified by the capture effect and retransmits its ID at slot 3. The transmission count of the tags is reduced by 1 by the ACK for TAG 2. Next, TAG3 with the transmission count 0 sends its ID at slot 4 and it is identified. TAG 4 and TAG 5 collide at slot 5 by trying to be identified simultaneously. The failed tags now select the transmission count randomly. TAG 4 with the transmission count 0 sends its ID at slot 6. However, the ID of TAG 4 is not identified correctly due to channel error. Then, tags recognize it as a collision. All tags increase their transmission counts by 1 except the tag with error. TAG 4 then retransmits its ID at slot 7. Thereader reserves two slots since channel error is considered as collision. So, slot 8 remains idle. Next, slot 9 is selected by only one tag TAG 5 and the tree stops.

III. Performance Evaluation

In this section, we analyze the number of time slots for identification under channel errors and the capture effect. First, we obtain the number of time slots used by the binary tree protocol under the ideal channel condition [16]. A binary tree is divided into two branches when the reader fails identification by a collision which occurs by sending the IDs from tags simultaneously. We calculate the number of total time slots from the time slots failed by a collision. We can find the number of time slots failed by collision by adding the number of time slots failed by collision at depth i of a tree when n tags try to be identified.

The number of total time slots under the ideal channel condition when n tags transmit their IDs is

$$T_{ideal}(n) = 2 \cdot F_{ideal}(n) + 1, \tag{2}$$

where $F_{ideal}(n)$ is the sum of the number of failed time slots at depth i when n tags try to send their IDs. The number of failed time slots at depth i can be obtained from the number of idle time slots and the number of successful time slots. The state of a slot can be classified into three types, i.e., successful slot, failed slot and idle slot.

The number of idle time slots at depth i under the ideal channel condition is

$$\begin{aligned} I_{ideal}(n,i) &= 2^i \binom{n}{0} \left(\frac{1}{2^i}\right)^0 \left(1-\frac{1}{2^i}\right)^n \\ &= 2^i \left(1-\frac{1}{2^i}\right)^n. \end{aligned} \tag{3}$$

The number of successful slots at depth i under the ideal channel condition is

$$\begin{aligned} S_{ideal}(n,i) &= 2^i \binom{n}{1} \left(\frac{1}{2^i}\right)^1 \left(1-\frac{1}{2^i}\right)^{n-1} \\ &= 2^i n \left(\frac{1}{2^i}\right)^1 \left(1-\frac{1}{2^i}\right)^{n-1}. \end{aligned} \tag{4}$$

The number of failed slots at depth i under the ideal channel is

$$F_{ideal}(n,i) = 2^i - I_{ideal}(n,i) - S_{ideal}(n,i). \tag{5}$$

The number of failed slots in a tree under the ideal channel is

$$F_{ideal}(n) = \sum_{i=0}^{\infty} F_{ideal}\,(n,i). \tag{6}$$

Thus, we can calculate the total number of time slots under the ideal channel condition.

Next, we derive the number of total time slots in the channel error condition with the capture effect. The number of time slots used for identification in the channel model with channel errors and the capture effect is

$$T_{capture}(n) = 2 \cdot F_{capture}(n) + 1. \tag{7}$$

The number of time slots failed by channel errors and the capture effect is the sum of the number of time slots at depth i when n tags compete.

$$F_{capture}(n) = \sum_{i=0}^{\infty} F_{capture}\,(n,i). \tag{8}$$

In order to find the number of failed tags at depth i in the channel model considering the capture effect, the number of successful tags by the capture effect is needed. So, we use the number of failed tags at depth i by the capture effect probability. We note that occurrence of the capture effect is affected by both noise and interference from neighbor tags. We find the probability of the capture effect from the Packet Error Rate (PER) considering both noise and interference. The signal to interference plus noise ratio (SINR) of tag j in the channel model with the capture effect is

$$\begin{aligned} &SINR(d_j, X_{coll}(k)) \\ &= \frac{P_{RX}(d_j)}{P_{noise} + \sum_{l \in \boldsymbol{X}_{coll}(k), l \neq j} P_{RX}\,(d_l)}, \end{aligned} \tag{9}$$

where $X_{coll}(k)$ is the set of k tags collided by sending their IDs simultaneously. So, $\sum_{l \in X_{coll}(k), l \neq j} P_{RX}\,(d_l)$ is the sum of received power of k collided tags.

Then the Bit Error Rate (BER) of tag j is

$$\begin{aligned} &BER(d_j, X_{coll}(k)) \\ &= 2Q\left(\sqrt{2^\sigma \cdot SINR\big(d_j, X_{coll}(k)\big)}\right)\left(1 - Q\left(\sqrt{2^\sigma \cdot SINR(d_j, X_{coll}(k))}\right)\right), \end{aligned} \tag{10}$$

where $Q(\cdot)$ is a Q function and σ is the line code index (σ=0 for FM0, σ=1,2,3 for Miller M=2,4,8). The PER is

$$\begin{aligned} &PER(d_j, X_{coll}(k)) \\ &= 1 - \big(1 - BER(d_j, X_{coll}(k))\big)^M, \end{aligned} \tag{11}$$

where M is the packet size in bits.

In order to consider the capture effect in the channel model with the capture effect, we obtain the probability of the capture effect. The probability of the capture effect of tag j when k tags collide is

$$\begin{aligned} P_{cap}(d_j, X_{coll}(k)) &= (1 - PER(d_j, X_{coll}(k))) \\ &\cdot \prod_{m \in X_{coll}(k), m \neq j} PER(d_m, X_{coll}(k)). \end{aligned} \tag{12}$$

We find the average capture effect probability considering the collision cases within R. Assuming the uniform distribution of tags, the average probability of the capture effect at depth i is

$$\begin{aligned} &P_{cap,avg}(n,i) \\ &= \sum_{k=2}^{n} \binom{n}{k} \left(\frac{1}{2^i}\right)^k \left(1-\frac{1}{2^i}\right)^{n-k} \\ &\cdot \int_0^R \cdots \int_0^R \frac{2\pi d_1}{\pi R^2} \cdots \frac{2\pi d_k}{\pi R^2} \cdot P_{cap}\big(d_k \cdot X_{coll}(k)\big) dd_1 \cdots dd_k. \end{aligned} \tag{13}$$

Then, the number of successful tags at depth i by the capture effect is

$$S_{cap}(n,i) = 2^i \cdot P_{cap,avg}(n,i). \tag{14}$$

The number of successful slots without channel errors at depth i when n tags try to send their IDs is

$$S_{capture}(n,i) = (1 - P_{fail}) \cdot (S_{ideal}(n,i) - S_{capture\_cm}(n, i-1)). \tag{15}$$

The number of cumulative successful slots at depth i when there are n tags is

$$S_{capture\_cm}(n,i) = \begin{cases} 0, & i = 0, \\ S_{capture\_cm}(n,i-1) + S_{capture}(n,i) + S_{cap}(n,i), & i > 0. \end{cases} \tag{16}$$

The number of cumulative successful slots at depth 0 is zero. At depth i, the number of cumulative successful slots is obtained from the sum of the number of cumulative success slots in the former depth, the number of success slots at the current depth and the number of success slots by the capture effect. Then,

$$F_{capture}(n,i) = F_{ideal}(n,i) + P_{fail} \cdot \frac{S_{capture}(n,i)}{(1-P_{fail})} - S_{cap}(n,i) \tag{17}$$

Thus, we can calculate the total number of time slots in the environment with channel errors and the capture effect.

We conduct performance evaluation of the proposed protocol and other protocols. The purpose of the proposed anti-collision protocol is to consider channel errors and the capture effect and to reduce the number of total time slots by identifying colliding tags immediately after the capture effect instead of future retransmission. The parameters of simulations are presented in Table 1.

Fig. 4 shows the performance of the proposed protocol, i.e., the number of time slots in the ideal channel condition and in the channel model with channel errors and the capture effect. The simulation results are matched with the analysis. The number of time slots used in the channel model with channel errors and the capture effect is more than that in ideal channel. When the number of tags is 1000, the RFID system in the channel model with channel errors and the capture effect consumes 53% more time slots than those in the ideal channel condition to identify tags. Since channel errors hinder tags to be identified appropriately, it may require more time slots due to retransmissions.

Fig. 5 shows performance comparison on the total number of time slots between the proposed protocol and other protocols, i.e., FSA, DFSA, and GBT under the channel model with channel errors and the capture effect. FSA identifies tags with the fixed frame size (i.e., 128 or 256). So, the performance of FSA is directly influenced by the frame size and the number of tags. DFSA repeatedly estimates the size of the next frame to identify tags without considering the capture effect. In addition, tags may not be identified by channel errors. DFSA regards the tags in channel errors and the collision as failed tags. GBT can identify tags in the capture effect condition. However, GBT repeats rounds to identify remaining tags after the capture effect until there are no remaining tags. The proposed protocol directly identifies the remaining collided tags right after the capture effect without retransmitting in the next round. As shown in Fig. 5, GBT consumes more time slots than the proposed protocol. GBT retransmits the collided tags and compete with new tags by the same probability. So, it tends to use more slots than the proposed protocol.

TABLE I. SIMULATION PARAMETERS

Parameter	Value
Reader's reading range (R)	10~15 m
Number of tags (n)	100~1000
Bandwidth	500 KHz
Frequency	900 MHz
Tag ID size (M)	96 bits
Thermal noise power spectral density	-174 dBm/Hz
Antenna characteristic (α)	1
Line code index (σ)	0 (FM 0)
Transmission power of a reader (P_{TX})	15 dBm
Antenna gain of a reader (G_{reader})	0 dBm
Antenna gain of a tag (G_{tag})	-6 dBm

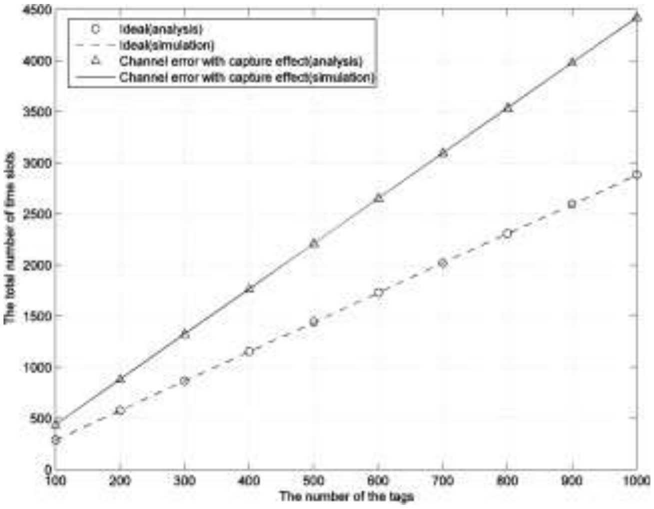

Figure 4. Comparison of the simulation with the analysis under channel errors and the capture effect (reader's reading range is 15m).

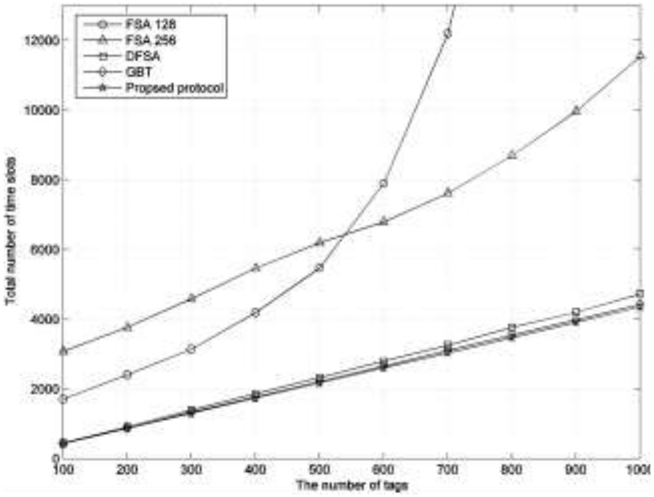

Figure 5. Performance of the total number of time slots with varying number of tags (reader's reading range is 15m).

Fig. 6 shows the number of time slots used by the proposed protocol with varying distance from 11m to 15m in the channel model with channel errors and the capture effect. In this figure, the markers represent analysis, and the lines represent

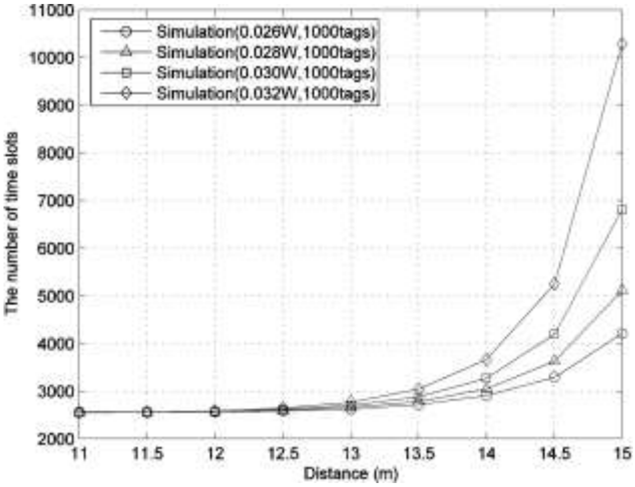

Figure 6. Performance of the number of time slots with varying distance from 11m to 15m when the number of tags is 1000.

simulation. Simulation and analysis are shown to be closely matched. The number of total slots by increasing distance rises rapidly starting from 13m since SINR is influenced by the distance in the channel model with the capture effect. When reader's transmission power is 15dBm (=0.032W) for 1000 tags, the proposed protocol with distance of 15m consumes about 53% more time slots than those with the distance of 11m. Also, the number of total slots varies by the transmission power since the received power at each tag drops by decreasing the transmission power.

IV. Conclusion

We have proposed an efficient tree-based anti-collision protocol for RFID systems to identify tags despite of channel errors and the capture effect. Our proposed protocol completes the identification process in one round without retransmission in subsequent rounds. The proposed anti-collision protocol can identify the collided tags right after the capture effect and it can improve the efficiency by identifying all of the remaining tags quickly. Thus the tags are identified in one round regardless of the capture effect. We model SINR to determine the interference caused by neighboring tags under the capture effect. Then, we derive the channel error probability and the capture effect probability. Performance evaluation shows that proposed anti-collision protocol consumes less slots than other protocols in the practical channel model with the capture effect.

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